DIFFERENTLY -TUNED VCO USING INDUCTIVELY COUPLED VARACTORS

Related Application

[0001] This application claims the benefit, pursuant to 35 U.S.C. 119(e), of the earlier filing date afforded:

[0002] U.S. Provisional Application Serial No. 60/460,330, entitled "Differentially "Bathtub" - Tuned CMOS VCO Using Inductively Coupled Varactors," filed on April 4, 2003 and which is incorporated by reference herein.

Field Of Invention

[0003] This application relates to Voltage-Controlled Oscillators and more specifically to oscillators with differential tuning based on inductively-coupled varactors.

Background Of The Invention

[0004] With the emerging market for the wireless LAN (local area network) standards, the need exists to provide radio solutions that integrate these standards together with the popular 802.11b standard into a single receiver. Preferably, a single VCO in combination with selectable frequency division capable of covering the 802.11a, b and g frequency bands, i.e., 2.4-2.5, 2.4-2.6 and 5.1-5.8 GHz, respectively, is needed. However, the obtainment of a wide VCO tuning range in combination with a low tuning constant K_{vco} is ever more challenging. A low K_{vco} is desirable for the PLL (phase-locked-loop) design and for the minimization of the VCO's sensitivity to noise and supply variations.

[0005] Band switching in addition to differential VCO tuning are known methods used to reduce the K_{vco} over the extended frequency range. Differential VCO tuning also provides significant reduction in up-converted common-mode (bias) noise into phase noise

and in the oscillator's sensitivity to supply- and bias variations. Several techniques exist to implement differential tuning. As the varactor's capacitance is determined by the voltage across its terminals, one can decouple a varactor capacitively from the oscillator's output nodes and bias both its terminals differentially. However, this will reduce the oscillation swing across the varactor, resulting in a highly non-linear tuning curve.

[0006] Alternatively, p-type and n-type varactors can be combined using simple NMOS and PMOS transistors in inversion mode. However, standard MOSFET transistors, used in differentially tuned VCO are not optimized for a maximum C_{max}/C_{min}-ratio or Q. Also, the C(V) curves of NMOS and PMOS devices are not well matched and can cause a loss of CMRR (Common-Mode Rejection Ratio), i.e. the circuit's ability to reject variations in its common-mode tuning levels that affect the frequency of oscillation.

[0007] Another approach is to use a combination of p- and n-type accumulation-depletion mode varactors. However, this requires a triple well process that adds to the cost. Finally, one could use only PMOS accumulation-depletion varactors, and connect the gates of one set of varactors to the outputs and tune it through the well side, and connect the well sides of a second set of varactors to the outputs and tune this set through the gate sides. However, in that case the oscillator is loaded with the large, low-Q parasitic capacitance between the well and the substrate; this will negatively affect the oscillator's phase noise and tuning range.

[0008] Hence, there is a need for a VCO differential tuning device, i.e, a tuner, that allows a VCO to be tuned differentially and that preserves maximum oscillation swing across the varactors and thus maximizes the tuning linearity of the VCO.

Summary Of Invention

[0009] A differently-tuned voltage controlled oscillator (VCO) and its application as a multi-band VCO tuner are disclosed. In one aspect of the invention, the VCO comprises a plurality of inductive elements, each comprising inductively coupled first and second inductor elements wherein corresponding ones of the first inductor elements and second conductor elements are connected in series, a varactor element connected in parallel with the serially connected first inductor elements, the varactor element comprising serially well-to-well connected first and second same-type varactors, each having a well side and a gate side, means to apply a first tuning voltage to a node common to the first inductor elements, wherein the first tuning voltage is applied to the gate-side of each of the first and second varactors through the first inductor elements and means to apply a second voltage to a node common to said well-side of said first and second varactors. In a second aspect, a second varactor element is connected in parallel with the second inductor elements associated with the inductive elements, the second varactor element comprises serially-connected same-type first and second varactors each having a well side and a gate side, and means to apply the second tuning voltage to a node common to the second varactor element first and second varactors, wherein the second tuning voltage is applied to the well-side of each of said first and second varactors.

Brief Description Of The Figures

[0010] Figure 1 illustrates a conventional differential tuner using n- and p-type varactors in accumulation mode;

[0011] Figures 2a-2c illustrate the operating characteristics of the tuner shown in Figure 1 when tuned in differential mode;

[0012] Figures 3a-3c illustrate the operating characteristics of the tuner shown in Figure 1 when tuned in common mode;

[0013] Figure 4 illustrates a first exemplary single-type differential tuner in accordance with the principles of the present invention;

[0014] Figure 5 illustrates an exemplary application of the single-type tuner shown in Figure 4;

[0015] Figure 6 illustrates a second exemplary embodiment of a single-type tuner in accordance with the principles of the invention;

[0016] Figures 7a-7c illustrate the operating characteristics of the tuner shown in Figure 6 operating in differential mode;

[0017] Figures 8a-8c illustrate the operating characteristics of the tuner shown in Figure 6 operating in common mode; and

[0018] Figure 9 illustrates another exemplary embodiment of a single type tuner in accordance with the principles of the present invention.

[0019] It is to be understood that these drawings are solely for purposes of illustrating the concepts of the invention and are not intended as a definition of the limits of the invention. The embodiments shown in the figures herein and described in the accompanying detailed description are to be used as illustrative embodiments and should not be construed as the only manner of practicing the invention. Also, the same reference numerals, possibly supplemented with reference characters where appropriate, have been used to identify similar

elements.

Detailed Description

[0020] Figure 1 illustrates a conventional dual type varactor differential tuner 100 including accumulation-depletion varactor stages 110 and 120, which are operable to output signals V_{out1} 130 and V_{out2} 140 on nodes 130' and 140', respectively. The frequency of signals V_{out1} 130 and V_{out2} 140, as is known in the art, is determined by the capacitance value of tuner 100, in combination with the fixed inductance across the nodes 130' and 140'.

[0021] Varactor stage 110 includes, in this illustrated example, dual PMOS accumulation-depletion varactors 112 and 114 and varactor stage 120, similarly, includes dual NMOS accumulation-depletion varactors 122 and 124. To illustrate the operation of the conventional dual type varactor, the contribution of PMOS varactor 112 to the single-ended capacitance seen from node 130' to ground, referred to as C_1, may be determined and adjusted by varying the value of a tuning voltage or potential 116, referred to as $V_{tunep,}$ that is applied through node 116' to the well-side of varactors 112 and 114. Similarly, the contribution of NMOS varactor 122 to the single-ended capacitance seen from node 130' to ground, referred to as C_2, may be determined and adjusted by varying the value of another tuning voltage or potential 126, referred to herein as V_{tunen}, that is applied at node 126' to the well-side varactors 122 and 124. A similar analysis may be performed to determine the contributions of PMOS varactor 114 and NMOS varactor 124 to the single-ended capacitance seen from node 140' to ground and need not be discussed in detail herein.

[0022] Figures 2a and 2b illustrate the small-signal capacitance as a function of voltage, i.e., C(V) curves, as a function of the difference, i.e., $V_{tunediff}$., between voltages V_{tunep} and V_{tunen}. i.e., tuning voltages. In one case, as shown in Figure 2a, as $V_{tunediff}$

increases, the value of the capacitance of C_1 210 and C_2 215 diverges and the width of the minimum in the C(V) curve, i.e., C_{tot} 220, also increases. In the case shown in Figure 2b, as $V_{tunediff}$ decreases, the value of the capacitance of C_1 210 and C_2 215 diverges and the width of the minimum in the C(V) curve decreases.

[0023] The large-signal output waveform V_{out1} cycles through these small-signal C(V) curves during each period of oscillation. As a result, the average capacitance experienced by the output V_{out1} and V_{out2}, which is not shown, determines the frequency of oscillation. In this case, as capacitance decreases the frequency of oscillation increases.

[0024] Figure 2c illustrates the change in the average capacitance of C_{tot} 220 , and consequently of the differential tuner 100, as a function of $V_{tunediff}$. As shown, in a "differential" mode of operation as $V_{tunediff}$ increases, the average capacitance decreases substantially and, hence, the frequency of V_{out1} 130 and V_{out2} 140 increases substantially .

[0025] Figures 3a and 3b illustrate the change in value of capacitances C_1 210 and C_2 215 as the combined value of V_{tunep} and V_{tunen}, commonly referred to as $V_{tunecomm}$, increases and decreases, respectively. For example, $V_{tunecomm}$ may be an average value of V_{tunen} and V_{tunep}. Figure 3c illustrates the change in the average capacitance of C_{tot} 220 as a function of $V_{tunecomm}$. In this common mode of operation, as the common voltage $V_{tunecomm}$ changes, the average capacitance remains substantially constant and, hence, the frequency of V_{out1} 130 and V_{out2} 140 remains substantially constant.

[0026] Figure 4 illustrates a first exemplary embodiment 400 of a single-type varactor differential tuner in accordance with the principles of the invention. In this illustrated embodiment, a first n-type varactor stage 410a, containing PMOS varactors 412a, 414a, is responsive to voltage V_{tunep} 116, applied through node 116' to the well-side of each

of the serially-connected PMOS varactors 412a, 414a. Second varactor stage 410b, containing PMOS varactors 412b, 414b, is responsive to voltage V_{tunen} 126, applied through node 126' to the gate-side of PMOS varactors 412b, 414b, through inductors 420b and 422b.

[0027] Inductive elements 420 and 422 electromagnetically couple varactor elements 412a and 414a in stage 410a to corresponding varactor elements 412b and 414b in varactor stage 410b. As shown, the windings of inductive elements 420a, 420b and 422a, 422b are reversed such that the oscillation signal, present at the gates of the varactor stage 410b, is inverted with respect to the oscillation signal, present at the gates of varactor stage 410a.

[0028] Thus, in this embodiment, the contribution of PMOS varactor 412a to the single-ended capacitance i.e., C_1, seen from node 130' to ground, and the contribution of PMOS varactor 412b to the single-ended capacitance, i.e., C_2, seen from node 130' to ground operates as discussed with regard to Figures 2a-2c for differential-mode tuning and Figures 3a-3c for common-mode tuning. Hence, as the varactor capacitance C_1 increases due to an increase in V_{out1} on node 130', the capacitance C_2 decreases, due to the signal inversion performed by the coupled inductors.

[0029] Further illustrated is voltage V_{bias} 430 applied at node 430'. Voltage V_{bias} 430 is provided to the common node of inductors 420a and 422a such that voltage V_{bias}, through inductor elements 420a and 422a, is superimposed on signals V_{out1} 130 and V_{out2} 140. V_{bias} 430 also provides a necessary current to a transconductor, as will be discussed with regard to Figure 5, that is needed to sustain the oscillation of signals V_{out1} 130 and V_{out2}. To ensure that the varactor stage 410b has a similar DC bias point as varactor stage 410a, the well-side of varactor section 410b is connected to the fixed voltage V_{bias} 430. The application of V_{bias} 430

to V_{out1} 130 and V_{out2} 140 allows a maximum amplitude variation about a non-zero DC-biased reference value equal to substantially one-half the supply voltage.

[0030] Figure 5 illustrates a schematic diagram 500 of an exemplary multi-band oscillator in accordance with the principles of the invention. In this exemplary application, the outputs of single-type varactor differential tuner 400, i.e., nodes 130' and 140', are coupled to bandswitcher circuit 510, and to negative resistance transconductor 515. Transconductor 515 is well known in the art to provide a negative resistance that compensates for losses in the circuit to maintain the oscillation of signals V_{out1} 130 and V_{out2} 140.

[0031] In this exemplary embodiment, the average or DC value of the voltage at the gate-side of varactor section 410a and the well-side of varactor section 410b are maintained at a fixed voltage determined by V_{bias} 430. In this illustrated example, V_{bias} 430 is maintained at roughly half the supply voltage V_{DD} due to the voltage drop across transconductor 515 resulting from a current that is supplied through current mirror 530. Tuning voltages V_{tunep} 116 and V_{tunen} 126 are applied about a common voltage level equal to half the supply voltage as well. This varactor biasing approach is advantageous as it assures a maximum differential tuning voltage range over which the oscillator may be tuned linearly. Thus, the output signal waveforms V_{out1} 130 and V_{out2} 140 are positioned symmetrical with respect to the sum of the C(V) curves, i.e., C_1 and C_2, thus giving the largest possible differential tuning voltage range over which the steep transition regions between the maximum and minimum capacitance values of curves C_1 and C_2 fall within the coverage range of the output waveform V_{out1} . This is related to the fact that the C(V) curve of the

accumulation-depletion varactor used is point symmetrical approximately around the point where the voltage between gate and well is zero volts as shown in Figures 2a and 2b).

[0032] Bandswitcher 510 allows, in this illustrated case, for four switched tuning bands that are binary controlled by voltage signals V_{sw1} 513 and V_{sw2} 515. Band-switching is implemented, in this case, by applying an appropriate voltage level to the well-side of the varactors in either or both of the varactor stages 512, 514. In this illustrated case, four states of band-switching are achieved by the application of combinations of the supply voltage, e.g., V_{DD}, or ground (e.g., 0 volts) to each of the varactor stages.

[0033] Current mirror 530 provides a bias voltage to tuner 400 as previously described with regard to Figure 4, i.e., bias voltage 430. Current mirrors are well-known in the art and need not be described in detail herein.

[0034] Figure 6 illustrates a second exemplary embodiment of a single-type varactor in accordance with the principles of the invention. In this illustrated embodiment, the circuit is identical to that of Figure 4, except that the windings of inductor 620b and 622b are reversed. In this case, the oscillation signals on the primary and secondary side of the coupled inductors are now in-phase. An analysis of the varactor small-signal capacitances now yields C(V) curves as depicted in Figures 7a-7c for differential-mode tuning and Figures 8a-7c for common-mode tuning.

[0035] With regard to Figure 7a, as the voltage $V_{tunediff}$ 130 increases, the capacitance of C_1 210 and C_2 215 shifts at a similar rate to the right in Figure 7a and the total capacitance C_{tot} 220 also shifts to the right in Figure 7a. With regard to Figure 7b, as the voltage $V_{tunediff}$ 130 decreases, the capacitance curves of C_1 210 and C_2 215 shift at a similar rate to the left in Figure 7b and the total capacitance C_{tot} 220 also shifts to the left in Figure 7b. Figure 7c

illustrates that the overall capacitance C_{tot} 220, averaged over one period of the oscillation waveform, yields an average capacitance $C_{avg.}$ that decreases as the differential tuning voltage increases in a manner similar to that shown in Figure 2c.

[0036] Figures 8a and 8b illustrate the change in total capacitance C_{tot} 220 as the voltage $V_{tunecomm}$ increases and decreases, respectively. Figure 8c illustrates that the overall capacitance C_{tot} 220 averaged over one period of the oscillation waveform yields an average capacitance $C_{avg.}$ that remains substantially constants as the voltage $V_{tunecommon}$ increases in a manner similar to that shown in Figure 3c.

[0037] Figure 9 illustrates a third exemplary embodiment 900 of a single-type varactor differential tuner in accordance with the principles of the invention. In this embodiment a single varactor stage 910b is tuned by applying at node 116' voltage V_{tunep} 116 to the well-side of serially connected varactors 912b and 914b. Electrically connected to the gate-side of varactors 912b and 914b is one end of inductor elements 920b and 922b, which are electrically connected in series. Voltage V_{tunen} is applied to a common node of inductors 920b and 922b, and thus applied to the gate-side of varactors 912b and 914b. Inductors 920b and 922b are electromagnetically coupled to inductors 920a and 922a, which are also connected in series. Voltage V_{bias} 430 is applied to a common node of inductors 920a and 922a and is thus superimposed on output voltages V_{out1} 130 and V_{out2} 140. In this illustrated embodiment, the voltage across the varactor, which sets the capacitance value of the varactor, is directly determined by the differential tuning voltage $V_{tunediff}$, i.e., $V_{tunep} - V_{tunen}$.

[0038] However, when V_{tunep} 116 and V_{tunen} 126 vary in common-mode manner, the voltage across the varactor does not change and thus the capacitance and frequency of oscillation remain substantially unchanged.

[0039] To ensure a maximum differential tuning voltage range over which the oscillator tunes linearly, again the common mode value of the tune voltages V_{tunep} 116 and V_{tunen} 126 are selected substantially equal to approximately half the supply voltage.

[0040] While there has been shown, described, and pointed out fundamental novel features of the present invention as applied to preferred embodiments thereof, it will be understood that various omissions and substitutions and changes in the apparatus described, in the form and details of the devices disclosed, and in their operation, may be made by those skilled in the art without departing from the spirit of the present invention. It is expressly intended that all combinations of those elements that perform substantially the same function in substantially the same way to achieve the same results are within the scope of the invention. Substitutions of elements from one described embodiment to another are also fully intended and contemplated.